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## Gravity and Extreme Magnetism SMEX (GEMS)

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### **Abstract**

The prime scientific objectives of the NASA Small Explorer mission, Gravity and Extreme Magnetism SMEX, or “GEMS”, are to determine the effects of the spin of black holes, the configurations of the magnetic fields of magnetars, and the structure of the supernova shocks which accelerate cosmic rays. In the cases of both stellar black holes and supermassive black holes, sensitivity to 1% polarization is needed to make diagnostic measurements of the net polarizations predicted for probable disk and corona models. GEMS can reach this goal for several Seyferts and quasars and measure the polarizations of representatives of a variety of other classes of X-ray sources, such as rotation-powered and accretion-powered pulsars. GEMS uses foil mirrors to maximize the collecting area achievable within the SMEX constraints. The polarimeters at the mirror foci are Time Projection Chambers which use the photoelectric effect to measure the polarization of the incident photon. We have built laboratory models with good efficiency and modulation in the 2-10 keV range. An attached small student experiment would add 0.5 keV sensitivity for bright soft sources. The instrument has a point spread function which allows measurement of structures in the brighter nearby supernova remnants. GEMS’ Orbital Sciences spacecraft will rotate at a rate of 0.1 revolutions per minute during observations, so that systematic errors due to the detector can be detected and corrected. A program of 35 sources can be observed in 9 months. GEMS is designed for a two year lifetime which will allow a General Observer program that would more than double the number of sources measured. For subsets of black holes, neutron stars and supernova remnants, GEMS will measure the polarization of several sources, solving important questions while establishing the sensitivity required for future missions.

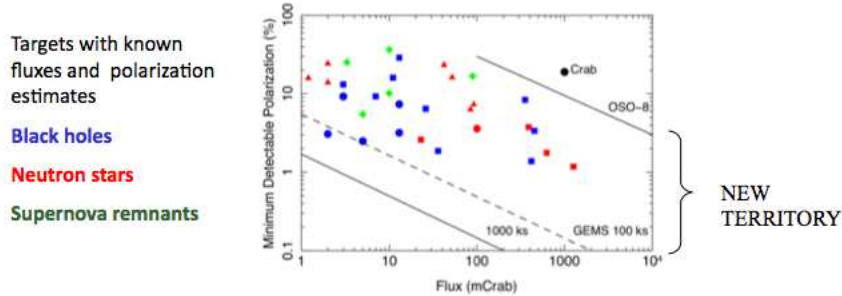


Fig. 1.1. GEMS Sensitivity and Discovery Phase Space. The minimum detectable polarization (MDP) at 99% confidence is shown for observations of  $10^6$  and  $10^5$  seconds. Possible values for polarization of proposed targets, according to some predictions, are shown at the known fluxes of the targets.

## 1.1 Introduction

The Gravity and Extreme Magnetism SMEX (GEMS) was proposed to NASA's 2007 SMEX AO in January 2008. It was one of 6 proposed missions selected for phase A studies. A study report was submitted in December 2008. The review continued during the spring of 2009 with presentations to the reviewers and selection officials to address questions. After this meeting on the Coming of Age of X-Ray Polarimetry, GEMS was one of two SMEX missions selected to have an opportunity for flight. In this paper, we describe the particular science objectives of GEMS that have defined the requirements for the mission. A program has been proposed, which will be reviewed before launch in consideration of what is known then. There are many other targets for which GEMS could be used. We give a brief overview of the instrument and the mission. The instrument depends on a polarimeter which uses the photoelectric effect. The polarimeter is a Time Projection Chamber. We briefly describe the polarimeter design and our demonstrations of its performance.

## 1.2 GEMS Scientific Objectives

### 1.2.1 A Sensitive Survey

At this point in the history of efforts to measure the polarization of the X-ray flux from astrophysical sources, still the only definitive measurements have been for the Crab nebula (1; 2). Integral has obtained provocative results for the Crab pulsar above 10 keV (3). Theoretical predictions between a few and tens of percent have been made for several types of black

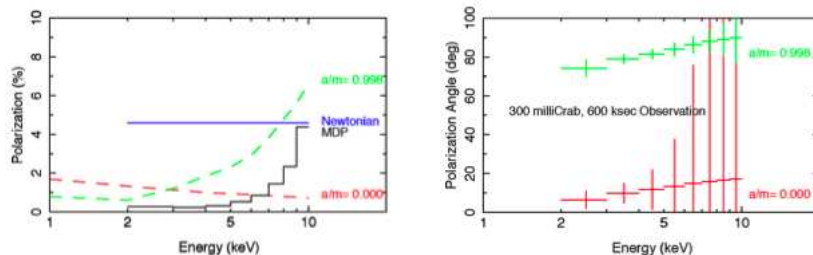


Fig. 1.2. General Relativity Effects on the Polarization. The GR predictions for accretion on a black hole in the high soft state are distinct from Newtonian predictions and, in GR, high and low spin are distinguished.

holes, neutron stars, and other supernova remnants. We are interested in answering questions about these sources. The GEMS sensitivity is shown in Fig. 1.1. This would open the frontier of X-ray polarimetry of the main emission from these sources, which is in the energy range 2-10 keV.

The predicted polarizations depend on several parameters in general. Several targets in a class should be observed to sample these parameters. We selected 15 black holes, 11 pulsars and neutron stars, and 6 supernovae remnants. (Pulsars in two supernova remnants and the Galactic center source Sgr B2 bring the number of targets to 35.) Plans for subsequent polarimetry missions would know which classes of sources turn out to have polarization that is most interesting and should be further explored. GEMS results would be a guide to the importance of polarization in this energy range.

### 1.2.2 Black Holes

Rees (1975)(4), near the beginning of X-ray astronomy, pointed out that x-ray polarization had been predicted by Chandrasekar for accretion disks. In 1980, Connors Stark and Piran (5) calculated the effects of a black hole on the polarization and angle. Their results were explored in more detail by Li *et al.* (2008) (6), using the same approach. Schnittman and Krolik (2009) (7) used a different approach and it makes a difference. The model of an optically thick disk accreting on to a spinning black hole can be specified in detail. The polarization and its angle determine the black hole spin and the disk inclination. This makes this type of target especially interesting. Fig. 1.2 shows simulations of possible results for a high state black hole of high inclination (75 deg).

Polarization is a degree of freedom that has not been available yet, to explore the geometry of X-ray sources. Modeling the X-ray spectral and

timing data for black holes in their hard states is still subject to frustrating uncertainty. Is the accretion in a spherical corona or a sandwich of a dense disk? There has not been consensus that all the data definitively picks out one or the other. Polarization measurements can resolve this ambiguity. Predicted levels of polarization are sensitive to the inclination angles of a geometrically thick scattering corona. AGN are the most challenging targets we have for GEMS, because most of them are relatively faint X-ray sources and the predicted polarization are mostly in the few percent range. We propose 6 Seyferts and quasars as part of our observing program, for observation times which can detect a level of 1% for the polarization averaged over the GEMS energy band.

### **1.2.3 Neutron Stars**

The proposed GEMS program includes neutron stars with pulsations arising from different mechanisms. Questions still attend the location of the x-ray emission in rotation-powered pulsars, in accretion-powered pulsars, and in magnetars. Anomalous X-Ray Pulsars and Soft Gamma Repeaters are both estimated to have fields on the order of  $5 \times 10^{14}$  gauss. The radiative transfer in the neutron star crust is expected to leave only the polarization perpendicular to the plane common to the magnetic field and the propagation direction. Van Adelsberg and Lai (2006)(8) have calculated the polarizations to be expected from the neutron star surface as it rotates about an axis. Magnetospheric fields are also estimated to be very strong in these sources and would give rise to polarization of the radiation emitted by plasma confined there. Pulse phased polarization will help define the geometry and determine the location of the emission, and test ideas about these sources.

### **1.2.4 Supernova Remnants**

X-ray polarization cinched the idea that the X-ray emission from the Crab Nebula was synchrotron radiation. Some remnants with clear shell structure and no identified pulsar wind nebula also have synchrotron emission from accelerated electrons, as indicated by power law spectra and TeV emission. From Suzaku and Chandra observations Uchiyama *et al.* (2007) (9) deduced that magnetic fields in the shocks were amplified from the swept up fields and that the synchrotron interpretation was secure. Questions remain about the way the fields are amplified and whether the fields in the shocks are turbulent. X-ray polarization will be an important diagnostic tool. The GEMS instrument does not image the sky, but the field of view is small compared

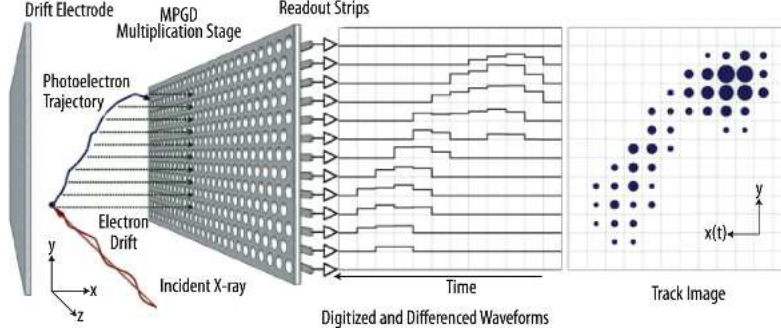


Fig. 1.3. Diagram of a TPC and the track reconstruction. The “y” coordinate comes from the strip number. The “x” coordinate from the relative arrival time of the signal. The track is made over a time very short compared to the drift time. The velocity of drift is calibrated from other measurements.

to the diameters of several supernova remnants and selective pointings can examine the polarization of the shells.

### 1.3 Overview of the GEMS Mission

#### 1.3.1 X-Ray Polarimeter Instrument

The GEMS primary instrument, the X-ray Polarimeter Instrument, or XPI, uses the photoelectric effect to measure the linear polarization of X-ray flux in the energy range 2-10 keV. It comprises 3 telescopes which focus source flux into photoelectric polarimeters which employ a Time Projection Chamber readout geometry and have been developed at GSFC for this application (Black *et al.* 2007(10)). The polarimeters record images of the photoelectron tracks produced after the absorption of X-rays. The initial direction of each track is correlated with the photon electric field direction; the distribution of directions from an ensemble of tracks gives the source polarization.

Costa *et al.* (2001)(11) first showed that gas detector development and read out technology had reached the point where photoelectrons in the 2-10 keV range could be tracked and the initial direction determined. This work was followed by development of thin Gas Pixel Detectors (e.g. (12)). The TPC detectors use the same effects, but with a geometry which allows the detector to have higher quantum efficiency.

Within the polarimeter, an X-ray ionizes a gas atom, usually ejecting a K electron, whose initial direction is correlated with the photon electric field, and an isotropically emitted Auger electron. The photoelectron loses energy within the gas, leaving an ionization track which drifts in a uniform field to

a Micro Pattern Gas Detector (MPGD) multiplication stage (a Gas Electron Multiplier) and a 1-D array of readout strips. Continuously sampling the output provides the second dimension of the track image. The data from these strips allows an image of the primary electron track to be reconstructed as indicated in the TPC diagram in Fig. 1.3. From this image the initial direction of the ejected electron is deduced.

The mirror focal lengths are 4.5 m. This was the focal length to the XRS instrument on Suzaku. The GEMS mirrors will be 33 cm, rather than the XRS value, 40 cm in diameter. The combined area of 3 telescopes is 510 cm<sup>2</sup> at 6 keV. The point spread function of these telescopes will be 1.5 arc minutes. The effective field of view is 12 arc minutes in diameter.

The XPI and the spacecraft bus rotate around the science axis at 0.1 rpm. Sub-milli-second time tagging of each event relates the track direction (measured in detector coordinates) to sky coordinates. The ensemble of track directions in detector coordinates is a sensitive measure of uncalibrated asymmetries in the detector response (and thus provides input to the calibration model). Since the experiment uniformly samples all sky angles at all detector angles, such asymmetries are effectively averaged out.

The SMEX program encourages the inclusion of student experiments which enhance the baseline mission. GEMS includes a student experiment from the University of Iowa. It uses the polarization dependence of Bragg reflection and the rotation of the instrument to provide additional sensitivity for bright soft sources, in a narrow window near 0.5 keV.

### ***1.3.2 Mission Design***

The SMEX missions are to be launched on Pegasus class rockets. Accommodation of the 4.5 m focal length requires an in-orbit deployment mechanism. GEMS employs a coilable boom supplied by ATK Space Systems. The mission is designed with a lifetime goal of 2 years, which is accommodated by an altitude of 575 km and an inclination of 28.5 deg.

The solar arrays are sized such that with the rotation, the pointing can be 90 deg  $\pm$  30 deg from the sun. This means that a given source on the equator can be observed for as much as 2 months, and higher latitude sources for longer periods. A given pointing position may be occulted by the earth every orbit and passage through the high charged particle regions of the South Atlantic Anomaly will interrupt data for minutes to a half hour during about half of the 15 spacecraft orbits each day. Taking an average efficiency estimate of 50 % good observing time, a 9 month observing program for 35 sources has been developed, which would sample 9 types of sources.

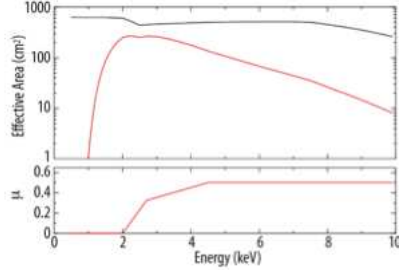


Fig. 1.4. GEMS performance characteristics. (upper) The total area of the 3 telescopes and the effective area when the polarimeter quantum efficiencies are taken into account. (lower) The modulation for a 100% polarized incidence flux.

Spacecraft operations will be conducted at the multimission operations center of Orbital Sciences Corporation, with data retrieved by a science operations center at Goddard. The data would be archived in HEASARC. Software will be developed within the FTOOLS system that is distributed by HEASARC. Calibration and examination of the data from a new instrument are estimated to take 6 months, after which data and results will be accessible from HEASARC.

If the proposed science objectives are achieved on schedule, the goal of a 2 year lifetime would make a a General Observer program possible.

#### 1.4 Polarimeter Performance

The TPCs will each have 4 MPGDs with a hexagonal pattern and pitch of  $140 \mu$ . The anode strips which detect the charge have a pitch of  $121 \mu$ . The MPGDs were developed by Riken and SciEnergy (Hayato and Tamagawa, this volume). Fig. 1.4 shows the effective area and the modulation for the configuration. The modulation was measured at 2.7, 3.5, and 4.5 keV and estimated at other energies, for 180 torr of Dimethyl Ether (DME).

The MDP shown in Fig. 1.1 for observations with a data accumulation time  $T$  has been calculated as  $MDP = (4.29/(\mu r))\sqrt{(r+b)/T}$ , where  $r$  is the source rate and  $b$  is the unrejected background rate. For a Crab-like spectrum the source rate will be  $0.64 \text{ counts s}^{-1}$  per mCrab. We have estimated that we can reject background events well enough that  $b$  will be negligible except for the weakest sources.

Fig. 1.5 shows a sample modulation curve of an engineering demonstration unit, which reads out the data with the APV25 ASIC selected for flight. This ASIC was designed by Imperial College and Rutherford Appleton Laboratories for use in the Compact Muon Solenoid (CMS) experiment at Cern. It provides continuous sampling at 40 MHz. The unpolarized data has been analyzed as it would be from a polarimeter on a rotating spacecraft.

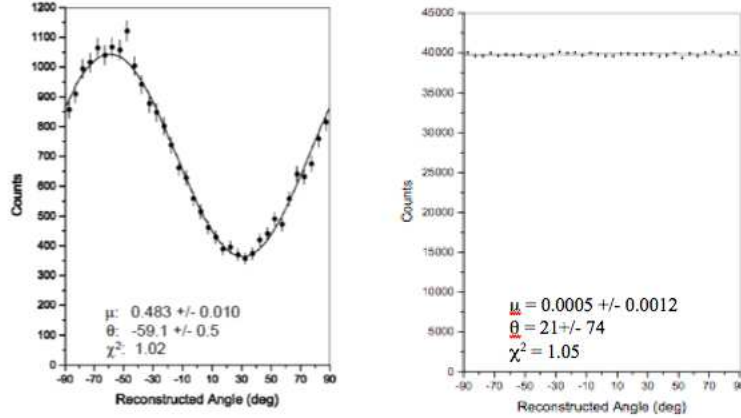


Fig. 1.5. Data from polarized and unpolarized sources. (left) The response to a polarized 4.5 keV line from Ti. (right) The response to an unpolarized 5.9 keV Fe55 source averaged over the simulated rotation of the detector.

## 1.5 Conclusions

Theories of stellar and supermassive black holes, strongly magnetic neutron stars and supernovae remnants have important unresolved questions. Polarization measurements can provide guidance. GEMS is a small polarization mission, now with a launch date in 2014, that can obtain significant results and prove X-ray polarization's usefulness.

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